Precision Profile Measurement of Microstructured Roll Workpieces

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論 文 内 容 要 旨

The measurement and the characterization of the surface profile of microstructued roll workpieces are becoming crucial to modern precision industries. The microstructued roll workpieces have advantages of a miniaturized size and a high accurate topography. Typtical applications of microstructued roll workpieces are: i micro gears for the power transmission, ii microstructured surface encoder for position measurement, iii master roll workpiece with microstructured patterns for the mass replication of microstructures. The workping performance of mechanisms and systems which are equipped with microstructured roll workpieces as functional components are primarily determined by the accuracy of the surface profile of the microstructured roll workpiece. Therefore, the surface profile measurement is used as an essential method for the quality control of components of the microstructured roll workpieces. Moreover, it is also can used by manufactures for achieving higher machining accuracy.

Commercially-available profile measuring instruments are primarily classified into five categories. They are coordinate measuring machines (CMMs), mechanical stylus profilers, scanning probe microscopes (SPMs), scanning electron microscopes (SEMs) and optical profilers. The CMMs are very effective tools for the profile inspection of workpieces, because the CMMs have no limit about the maximum detectable slope and can be easily operated. Ruby ball probes are usually equipped by the CMMs. The tip radius of the ruby ball probe is limited to hundreds of micrometers. Therefore, the applicability of the CMMs is affected by the curvature radius of the ruby ball probe. The microstructured roll workpieces have concave parts which should be measured. In these concave parts, the width and the depth of the space allowed for the probe are in the range from tens of micrometers to hundreds of micrometers. Therefore, for the surface profile measurement of the microstructured roll workpieces, the probe of the CMM cannot access the measured surface. Even if it barely accessed the measured profile, amount of immeasureable area, of which the curvature radius is smaller than probe tip, would occur. Mechanical stylus profilers are other type of robust instruments for the profile inspection of workpieces. They have merits of a large measurement range and a small measurement resolution of sub-nanometers. The typical measuring force of the mechanical stylus profilers is 1 mN. Generally, the mechanical stylus profilers employ a conical type of a diamond-tipped stylus, of which the tip radius can be reduced to be micrometers even sub-micrometers. The included angle of the diamond-tipped stylus is 90 degrees or 60 degrees. That means the maximum detectable slope of the mechanical stylus profilers is 45 degrees or 60 degrees. However, the maximum local slope of the microstructured roll workpieces is up to 70 degrees even 90 degrees, which is challenging the measurement capability of the mechanical stylus profiler. Furthermore, experiments have confirmed that while the microstructured roll workpiece is measured by the mechanical stylus profiler, a phenomenon of the stylus jumping motion and the kinematic interference between the stylus flank and the measured profile would appear and result in unacceptable distortions for the measurement. SPMs represented by atomic force microscopes (AFMs), which have extremely high spatial resolutions of sub-nanometers, are popular measurement instruments among the semiconductor industry. The AFMs usually employ piezoelectric actuators as a scanner and a micro-electro-mechanical-systems (MEMSs) based micro stylus with a tip radius of nanometers. Therefore, the vertical and the horizontal measurement ranges are limited in tens of micrometers, which are not satisfy the requirement of the surface profile measurement of the microstructured roll workpieces. The SEMs employs fine beam of electrons to scan the specimen. Backscattered electrons generated by the measured specimen are collected, amplified and analyzed. The output of the SEM measurement result is a two-dimensional image with a much higher horizontal resolution than optical instrument. The measurement range of the SEMs is relatively larger than the SPMs and the optical instruments. However, the SEMs are essentially a two-dimensional technique, although the vertical dimension information is given by gradient colors obtained by specialized algorithms. Therefore, the SEMs usually employed to observe not quantitative measure the surface profile of the measurement specimen. Typical optical surface profilers consist of confocal microscopes, autofocus microscopes and white light interferometers and are characterized by nondestructive to the measurement specimen. However, their maximum detectable slopes are limited 15 degrees and 30 degrees for the auto focus microscopes and white light interferometers, respectively. Although the maximum detectable slope of the confocal microscope is up to 75 degrees, it is also not proper to measure the surface profile of microstructure arrays with steep local slopes. Therefore, the optical surface profilers are generally used the measurement specimen with a relative smoother surface. Moreover, the optical surface profilers are much effective to detect the planar surface, because the optical surface profilers employ planar scanners.

In this dissertation, for precision profile measurement of microstructured roll workpieces, two rotary measuring systems, which primary consist of an air-bearing displacement sensor, a diamond-tipped micro stylus probe and a precision spindle/an air-bearing spindle, and advanced measurement strategies have been proposed. In the research, the rotary measuring system based on the precision spindle has been applied on the surface profile measurement of a roll workpiece with external microstructures. By introducing the wavelet analysis method, the error components, which influence the measurement precision, have been indentified out. For enhancing measurement accuracy, methods of setting error compensation and probe tip radius correction have developed and investigated by simulations. An ultra-precision rotary measuring system, which is based on an air-bearing spindle, also has been constructed. Roll workpieces with internal microstructures and external microstructures have been measurement by the two rotary measuring systems; and measurement results have been compared and analyzed. In order to quantitatively describe the measurement accuracy of the two measurement systems, a gear-shaped master artifact has been employed as a specimen for pitch deviation measurement, which is based on the surface profile measurement of the gear-shaped master artifact. The measurement accuracies of the two measurement system have been calibrated by experiments as well as a theory analysis.

In Chapter 1, general backgrounds and motivations have been described for the precision profile measurement of microstructured roll workpieces. Then, reviews of the conventional measurement methods and their characteristics have been presented and analyzed. Aims of this research and the approaches for achieving the goals have been given out at last.

In Chapter 2, the rotary measuring system based on a precision spindle has been constructed and applied on the surface profile measurement of a microstructured roll workpiece. The measuring force of the system is smaller than 0.45 mN; the maximum detectable surface slope of that is up to 80 degrees; and the angular positioning resolution is 0.15 arc-second. Regarding the measured microstructured roll workpiece, the nominal pitch of the microstructures is 100 μm, the nominal amplitude of that is 50 μm and the maximum local slope of that is 70 degrees. In order to confirm advantages of the constructed measurement system, the specimen also has been measured by two commercially-available measurement systems, which are a mechanical stylus surface profiler and a scanning type confocal microscopy. Measurement results of the constructed rotary measurement did not show noticeable noises and distortions, which could be observed in the measurement results of the two commercially-available measurement systems. Results of data analysis have shown that the repeatability accuracy of the system is related to the rotational scanning speed of the direct drive motor. The measurement repeatability errors of the system were approximately ±200 nm, ±300 nm, and ±400 nm for the rotation speeds of 0.1 rpm, 0.2 rpm and 0.3 rpm, respectively. The maximum repeatability errors occurred when the stylus probe was ascending the microstructures. The wavelet analysis method, which has a capability to indentify the frequency feature of signals in time domain, has been introduced to analysis the repeatability error. It has been confirmed that the main components of the repeatability errors have a frequency features of 50-51Hz, 71-73 Hz and 106-109 Hz.

In Chapter 3, setting errors, which primary consist of the offset error of the sensor axis, the zero point error of the sensor output and the eccentric error, have been considered deeply influence the measurement accuracy. Corresponding geometrical model and mathematical model have been established. The detection method and the compensation method have been proposed for the setting errors. Accuracy of the setting error compensation has been investigated by simulation and confirmed to be smaller than 10 nm. Another type error caused by the probe tip radius also has been analyzed. A 1st linear fitting method has been proposed to correct it. The correction accuracy has been confirmed to be smaller 3 nm for the errors of the probe tip radius. Based on the methods to detect and compensate the setting errors and the method to correct the errors of the probe tip radius, the advanced measurement strategy has proposed for the surface profile measurement of microstructured roll workpieces.

In Chapter 4, an ultra-precision rotary measuring system based on an air-bearing spindle has been constructed for the surface profile measurement of microstructured roll workpieces. For clarity, the angular positioning resolution is reduced to 0.0086 arc-second, which is about 1/18 of the previous one. A roll workpiece with external microstructures and a roll workpiece with internal microstructures have been measured by this rotary measurement systems based on the measurement strategy proposed in Chapter 3. Measurement results have shown that measurement repeatability is smaller than 200 nm for the roll workpiece with external microstructure and smaller than 180 nm for the roll workpiece with internal microstructures.

In Chapter 5, a gear-shaped master artifact, of which the nominal amplitude is about 4 mm and the maximum local slop is 90 degrees, has been employed as a measurement specimen to evaluate two proposed rotary measurement systems. The measurement target has been set to be the single pitch deviations and the cumulative pitch deviations. The pitch measurement strategy is based on the surface profile measurement of the gear-shaped master artifact. An opposite-direction dual scanning method, which has a capability to overcome the limit of 80 degrees detectable angle, has been developed for the surface profile measurement of the gear-shaped master artifact. For the surface profile measurement of the master artifact, the measurement repeatability is ±2.5μm for the rotary measuring system constructed in Chapter 2, and the measurement repeatability is ±300nm for ultra-precision rotary measuring system. The measurement results of the pitch deviations obtained by two rotary measurement systems have deviations in range of 0.12 μm to 1.49 μm, which line in error allowance indicated by their corresponding measurement uncertainties. For the rotary measurement system based on a direct drive motor, the calibrated uncertainties are 1.21 μm, 1.05 μm, 2.99 μm and 2.55 μm for the left flank and the right flank of the single pitch deviations and cumulative pitch deviation, respectively; and those values are 0.25 μm and 3.14μm in the theory analysis. For the rotary measurement system based on an air-bearing spindle, the calibrated uncertainties are 0.96 μm, 1.12 μm, 1.91 μm and 2.05 μm for the left flank and the right flank of the single pitch deviations and cumulative pitch deviation, respectively; and those values are 0.05 μm and 0.39 μm in the theory analysis. These results have implied that the air-bearing spindle based rotary measuring system has good measurement accuracy and measurement precision that the other one.

In Chapter 6, conclusions and achievements of this thesis are discussed.

論文審査結果の要旨

近年，微細構造を持つロールワークは精密機械のコアパーツとして，その形状精度は機械の性能に大きく影響を与える。ロールワークの微細形状の超精密測定は品質保証のほか，加工精度の限界を突破するのに必須な技術でもある。本論文は，微細構造を持つロールワークの精密形状測定に関する研究をまとめたものであり，全編 6 章からなる。

第 1 章は緒論であり，本研究の背景，目的および構成を述べている。

第 2 章では，微細構造を持つロールワークに適する極座標回転型精密計測法の開発について述べている。微細構造を持つロールワークの表面は，70 度以上の表面傾斜角，急峻な形状曲率変化といった極峻な表面幾何学特徴を持つため，従来の計測技術ではその測定は困難となっている。この形状の高精度測定を実現するために，極低測定力 (0.45 mN)，長測定範囲 (14 mm)，サブナノメートルの超高分解能 (0.14 nm) を有するエアベアリング型変位センサを開発している。この変位センサと回転機構，そして直動機構からなる走査系を組み合わせることで，微細構造を持つロールワークの計測システムを構築し，目標の 1μm より高い 0.3 μm の測定繰り返し精度を実現している。これは微細構造を持つロールワークの表面形状測定にとって有益な成果である。

第 3 章では，微細構造を持つロールワークの形状測定における測定対象及び変位センサのセッティング誤差を自律的に校正する方法の開発について述べている。測定結果に大きな影響を与える誤差要因として，セッティング誤差を高精度に校正する必要があるが，高い精度の外部基準と測定装置を必要とする従来法ではその実現が困難であった。本研究では，微細構造を持つロールワークの形状測定データからセッティング誤差を算出するという自律校正法を提案し，外部基準及び測定装置を用いない形でセッティング誤差を補正することに成功している。これは，理論的にも実用的にも価値の高い成果である。

第 4 章では，エアベアリングスピンドルを採用した超精密計測システムの開発について述べている。回転型計測システムにおいて，回転機構の回転位置分解能と回転運動精度が微細形状の測定精度を左右する最も重要な要素である。本研究では，回転運動精度に優れるエアベアリングスピンドルを回転機構として採用し，その回転位置を 0.0087 秒の超高分解能を持つロータリーエンコーダで計測することにしている。エアベアリングスピンドル，エアベアリング型変位センサ及びセッティング誤差の自律校正法を融合させることによって，超精密計測システムを構築している。その結果，0.1 μm オーダの全周測定繰り返し精度を実現している。これは，次世代超精密ロールワーク計測への対応を可能にした重要な成果である。

第 5 章では，提案した極座標回転型精密計測法による高精度歯車の形状測定について述べている。微細構造を持つロールワークの代表的な部品としての歯車は，その表面傾斜角は局所的に 90 度まで大きくなるので，従来の測定装置ではその全周形状を計測することができない。本研究では，マルチ走査機構を開発し，90 度の傾斜角まで対応できる測定手法を提案している。さらに，計測した全周形状データから，歯車のピッチ誤差を算出するアルゴリズムを開発し，その計測不確かさの評価を行っている。第 4 章で述べた超精密計測システムにおいて計測実験を行った結果，単一ピッチ誤差と累積ピッチ誤差をそれぞれ 0.048μm，0.392 μm の不確かさで計測できていることが確認されている。これは開発した計測システムの有効性を実証した成果で，高く評価される。

第 6 章は，結論である。

以上要するに，本論文は微細構造を持つロールワークの表面形状を超精密に測定するための新しい計測手法及びそれに基づく計測システムを実現したものであり，ナノメカニクスおよび生産工学に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。